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The Uncertain Future of Global Freshwater Resources

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The Uncertain Future of Global Freshwater Resources

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Dedication

I dedicate this work to those students who come after me, particularly those eager to find ways to provide fresh water to all the people of the world.

Acknowledgements

I would like to thank the many people who have worked with me throughout the entirety of my graduate school career and who have helped guide me into the completion of this report: my always patient parents and brother, my fiancé and his family, and the friends who have surrounded me with support and encouragement since I began at the University of Texas. I would also like to thank the many professors I've studied beneath at the Jackson School of Geosciences, as well as my supervisor, Joel P. Johnson, for their availability and eagerness to teach.

Abstract

The Uncertain Future of Global Freshwater Resources

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The University of Texas at Austin, 2015

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Projections regarding the future of conditions on Earth vary widely. Climate change, both human-induced and naturally-forced, is expected to have many far-reaching implications, including altering current global weather patterns and terrestrial freshwater supply. Already, terrestrial water fluxes have been affected by human demand and interventions. Examples of human-induced impacts include dam and reservoir building, water withdrawals from ground and surface water for agricultural, industrial, and municipal use, as well as environmental sanitation impacts. Since the 1970's, concurrent with rising global mean temperature, freshwater discharge from rivers to the world's oceans has been decreasing.

In the United States, the Southwest (from the headwaters of the westernmost Colorado River to the Mexican border, encompassing California, Nevada, Utah, and Colorado) has experienced three extreme drought years since the start of the 21^{st} century. Projections indicate that precipitation over the lower mid-latitude continental regions,

including the southwestern United States, will continue to decrease as a result of continuing greenhouse gas emissions and increasing global mean temperature. Colorado River flow reached the ocean in mid-2014 as part of a restorative experiment agreed to by the United States and Mexico, but had not previously reached the ocean since 1998. Rivers in Australia, Africa, and Asia are experiencing the same phenomena, with human extraction impairing the river's natural ability to meet the sea. There are political and technological techniques that could mediate regional decreases in freshwater supply. In particular, large changes in agricultural use are necessary to compensate for oncoming climate shifts and to ensure that the worldwide population has access to enough water for survival.

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Introduction

Discussions about the future of water resources have been occurring for centuries, with modern concerns centering on the risks associated with a changing climate. Adaptive steps to counter projected changes or actions to change human behavior in order to preserve resources have been inadequate for offsetting anticipated shortages in freshwater availability in some regions of the world. In the United States, people living in the south or the west will experience the effects of drought periods at home, since the knowledge of most people is local, but future changes are projected to occur globally. This study is intended to close the gap in knowledge and enhance comprehension about the global state of water resources, while also encouraging interest in the state of water resources "at home" in the southwestern United States. The following sections will begin by widely describing the state of global water availability and the changes that are projected to occur due to human influence and global warming. Next, case studies from three different continents are discussed to give a more detailed description of projected changes on a smaller scale. Finally, an in-depth look at the current state and projected changes for the Colorado River in the southwestern United States is presented.

Global Changes in Water Availability

Climate models project future global changes to the current patterns of water supply, while demographic projections indicate continued increases in demand. Simultaneously, human-induced impacts, from activities such as the dam construction and water withdrawals from ground and surface water are already altering the status of water supplies. The combined effects of impacts from current human influences and demands on resources are significant and place extreme pressure on water resource systems. The anticipated climate variation and projected large-scale irreversible changes herald chronic effects and critical scarcity in the future. In fact, environmental changes are already taking place; concurrent with increases in global mean temperature, freshwater discharge to the oceans has been decreasing since the 1970's (Cayan et al., 2010; Dai et al., 2009). Future change in river runoff, a proxy for renewable water resources, is linked to changes in precipitation and temperature, which are driven by global greenhouse gas emissions (Tang and Lettenmaier, 2012). Unlike runoff, which can be managed, the consumption of nonrenewable water resources is highly unsustainable. Once a society exhausts their nonrenewable resources, their vulnerability to water scarcity is exacerbated. Furthermore, water resources are frequently transboundary by nature with the result that one country has the potential to be affected not only by changes within its boundaries, but changes in upstream water use and supply as well, (Milman et al., 2013).

Globally, there is an average of 42,750 km^3 of renewable water available to use each year, with the majority of available resources located in Asia and South America, leaving Europe and Australia with the smallest volumes of water (Shiklomanov, 2000). The distribution of water resources, however, does not match the distribution of the world's population; as a result, people living in heavily populated areas are vying for fewer resources in competition with massive numbers of people. More than 40% of global river runoff originates in Brazil, Russia, Canada, the United States, China and India. However, China, India, and the United States are also the three most populated countries in the world, with Brazil and Russia placing fifth and ninth respectively (Shiklomanov, 2000; United States Census Bureau, 2015). Global water is always moving, as the water cycle transports water (in the form of precipitation) from continental interiors to the world's oceans and back. It typically moves water to a different place than where it evaporated. From 1920 to 1985, there was a trend of decreasing water availability in Africa and increasing availability in South America (Shiklomanov, 2000). Seasonality is also important: many of the world's rivers experience flooding as a result of seasonal snowmelt or monsoons; therefore water is only readily available for a portion of the year. In an average year, 46% of river runoff worldwide occurs between May and August (Shiklomanov, 2000).

From 1901 to 2010, precipitation increased in eastern North America, southern South America, northern Europe, northern and central Asia, and parts of Australia. Over the same time period, however, precipitation declined in the Sahel of Africa, the Mediterranean, southern African and southern and eastern Asia, with much of the change in precipitation evident since 1951 (Figure 1) (IPCC, 2013). Globally, areas experiencing drought have expanded since the 1970s coincident with increasing frequency of heat waves, rising global temperatures, and decreasing snow and ice cover (IPCC, 2013). Future projections, based on global hydrological models and general circulation models, as well as emissions scenarios, include the likely possibility of precipitation increasing at high latitudes and some mid-latitudes, but declining or continuing current patterns of decline over the Middle East, the Mediterranean, southern North America, southern Africa, and southern Australia (Figure 2) (Hagemann et al., 2013; IPCC, 2013). Evapotranspiration is expected to follow the same pattern, but the increase is expected to spread further southward, with the absolute values of evapotranspiration depending on the emissions scenario (more emissions lead to higher evapotranspiration) (Hagemann et al., 2013).

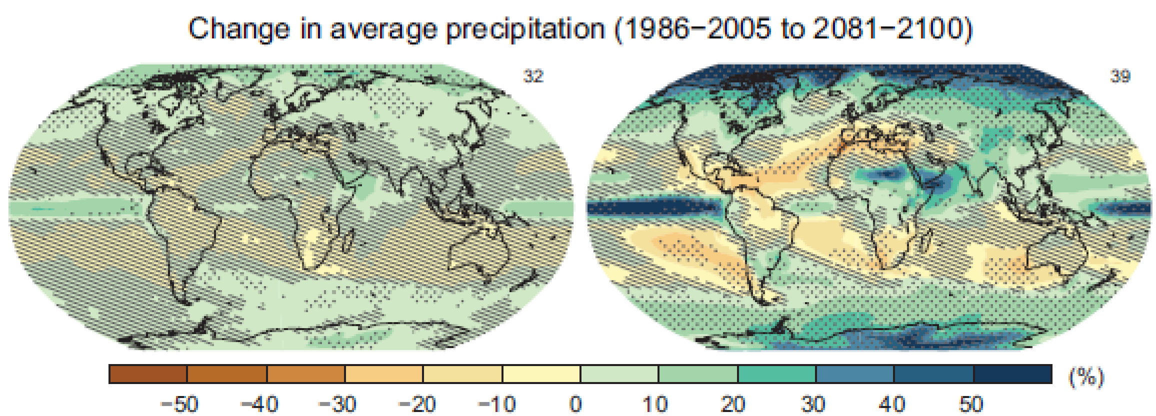

Figure 1: Percent change (%) in average precipitation worldwide from 1986 to 2005 (left) and projected changes for 2081-2100 (right), from IPCC (2013).

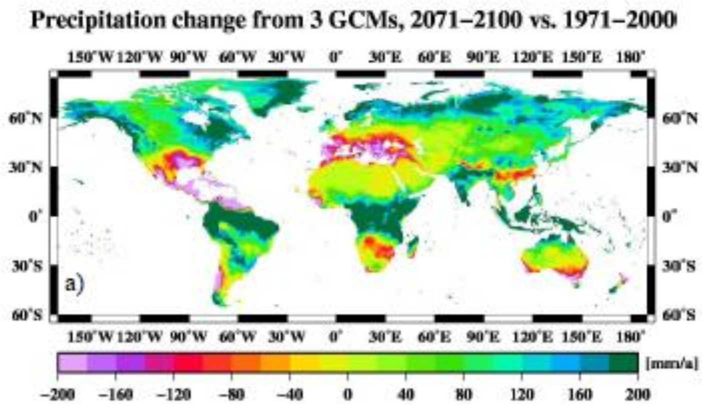

Figure 2: Changes in average precipitation (mm/year) projected by three global climate models following the A2 IPCC emissions scenario for 2071-2100 compared to the 1971-2000 average, from Hagemann et al. (2013).

The greatest runoff decreases are projected in areas that are already arid or semi-arid and the number of river basins in which runoff is expected to decrease will likely increase as mean temperature also increases, affecting larger and larger populations and negatively impacting gross domestic product (GDP) (IPCC, 2013; Tang and Lettenmaier, 2012). Global climate models agree that available water is expected to decline in semi-arid basins such as those in central, eastern, and southern Europe, and the Tigris, Euphrates, Mississippi, Xhu Jiang, Murray-Darling, Okavango, and Limpopo River basins (Figure 3) (Hagemann et al., 2013).

In many cases, however, models do not include human interventions when making projections for the future, and therefore human construction (dams) and withdrawals (e.g. for irrigation) are not taken into account (Hagemann et al., 2013). This can, then, inherently lead to error within projections for the future of terrestrial water. Humans do not adhere to the rules of nature: water can be removed from dams whenever a society feels the need, not necessarily when nature would dictate. This unpredictability can lead to further error in estimates of future water need and availability. Additionally, water withdrawals from one location may end up somewhere else entirely, leading to further consequences where the water is removed, but lessening the consequences (or delaying the inevitable) for the location to which the water is relocated. Societies tend to be built upon the assumption that where water once was, it will always be, however as water availability continues to decrease, many locations will have to cope with the fact that water will not always be available and use local conservation techniques to maintain some supply (Fishman, 2011).

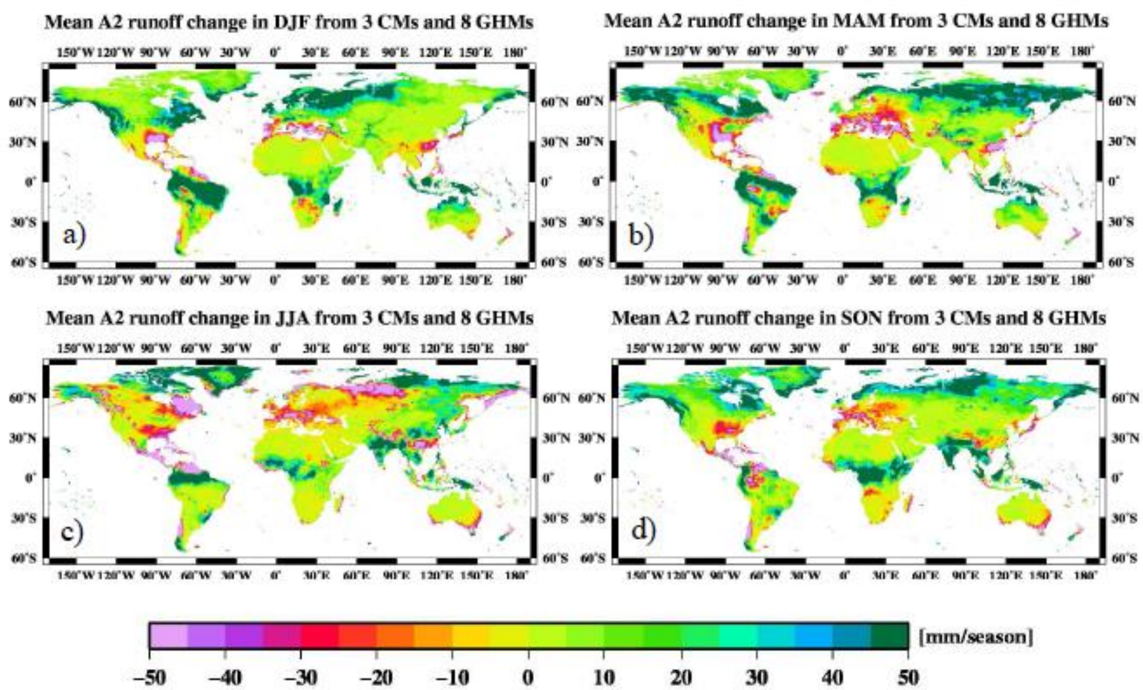

Figure 3: Seasonal changes in runoff (mm/season) projected by global hydrological models and global climate models following the A2 IPCC emissions scenario for 2071-2100 compared to the 1971-2000 average. Each panel shows season: a) December, January, February, b) March, April, May, c) June, July, August, d) September, October, November, from Hagemann et al. (2013).

Models by Vörösmarty et al. (2000) were run using data and projections based on 1985, with the hope of determining the future state of global water resources in 2025, as affected by both climate change and human development. In 1995, one-third of the global population lived under conditions of water scarcity and 450 million were under severe water stress. By 2000, the population living in severe water stress conditions evolved to 1.76 billion people (Vörösmarty et al., 2000). By 2025, 80% of the world's population could face similar severe water stress conditions (Shiklomanov, 2000). It is an important assumption that humans have access to the mean annual surface and shallow aquifer runoff in the form of river discharge to use for domestic, industrial, and agricultural purposes. For the purposes of these models, water extraction is coming solely from rivers rather than nonrenewable groundwater. Model results showed that mean global runoff varied due to climate change from an increase of <1 mm/year to a decrease of 17 mm/year, but larger changes were found at both local and regional scales (Vörösmarty et al., 2000).

Three scenarios were considered: (1) varying climate but fixing the magnitude and distribution of population and water use at the 1985 level, (2) maintaining the contemporary climate, runoff, and discharge but applying projected water demands for 2025, and (3) changing climate and water demands, a combination of both prior scenarios (Vörösmarty et al., 2000). Total per capita water use is projected to decrease from 640 to 580 m^3/year between 1985 and 2025, however the global population is expected to increase. Therefore, in scenarios 2 and 3 the impacts of human development do not reflect the intensification of water use, but the effect of population growth and worldwide migration (Vörösmarty et al., 2000). Results from scenario 1 show little difference from climate projections, as would be expected. Results from scenario 2 show an 85% increase in the vulnerable population from 1985 to 2025 (Figure 4). Upon investigating agriculture, Vörösmarty et al. (2000) discover that the number of people dependent on irrigated lands in areas of high water stress increases by over 33% (Table 1). This reflects the growing global population, as irrigation is expected to sustain the same percentage of the population as in 1985 (40%) but with much less water availability.

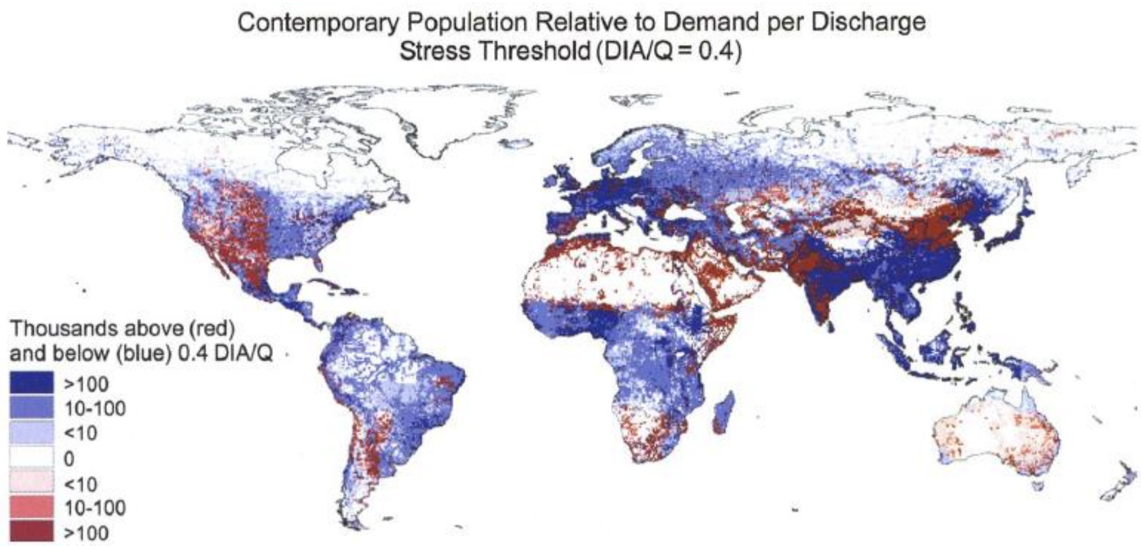

Figure 4: The distribution of global population in 1985 experiencing high or low water stress. A DIA/Q value of 0.4 or greater is indicative that a population is undergoing severe water scarcity (indicated in red shades). As this figure was created using 1985 population and water use statistics, it is likely that the highly stressed areas have expanded with growing population and increasing usage, from Vörösmarty et al. (2000).

Building upon the research of Vörösmarty et al. (2000), Alcamo et al. (2007) use two Intergovernmental Panel on Climate Change (IPCC) emissions scenarios (scenario A2 shows increasing greenhouse gas emissions and B2 shows a much slower rate of climate change) to determine the significance of climate change and anthropogenic water withdrawals on future water availability. Both the A2 and B2 scenarios show that water will become less available as time passes. Half of the population of northern Africa and the Middle East is already experiencing extreme water scarcity conditions (< 500 m^3 water yearly per capita) (WWAP, 2015). In 1995, 21.6% of global river basin areas were experiencing severe water stress conditions (withdrawals > availability), but by the 2050s severely water stressed areas are projected to cover 26% of the globe (Alcamo et al., 2007). Furthermore, over 60% of global river basin area will experience increasing water stress through the 2050s, while less than 30% will experience lessening stress due to increased precipitation and water-use efficiency (Alcamo et al., 2007).

A DI/Q (unitless)	Cumulative population (billions)			
	Con-temporary	Sc1	Sc2	Sc3
1.0	0.9	0.8	1.9	1.6
0.4	1.2	1.0	2.4	2.2
0.2	1.4	1.3	2.8	2.7
0.1	1.7	1.6	3.2	3.2
0.01	2.9	2.9	5.4	5.4
0.001	4.1	4.1	7.0	7.0
0.000	4.8	4.8	8.0	8.0

B A/Q (unitless)	Cumulative dependent population (billions)			
	Con-temporary	Sc1	Sc2	Sc3
1.0	1.5	1.4	2.7	2.7
0.4	1.9	1.8	3.4	3.3
0.2	2.2	2.1	4.0	3.9
0.1	2.6	2.5	4.7	4.7
0.01	3.8	3.8	6.7	6.6
0.001	4.5	4.5	7.6	7.6
0.000	4.8	4.8	8.0	8.0

Table 1: The distribution of global population and their domestic and industrial water needs over the water supply (A) and agricultural needs over water supply (B) in three different scenarios. DI/Q and A/Q of 0.2 to 0.4 indicate medium to high water stress and DI/Q and A/Q of 0.4 or greater indicate sever water stress. Scenario 1 (Sc1) changes climate but holds population needs steady at 1985 levels, scenario 2 (Sc2) holds the climate at 1985 levels but uses projected water needs for 2025, scenario 3 (Sc3) is a combination in which both climate and water needs change, from Vörösmarty et al. (2000).

Areas in which withdrawals and consumption greatly outstrip water availability (runoff) by the 2050s include northern and southern Africa, the Middle East, central and southern Asia, the southwestern United States, and parts of western and northeastern South America (Figure 5) (Alcamo et al., 2007). The total population projected to be living in severely water stressed regions by the 2050s ranges from 4.63 to 6.92 billion people (48% to 72% of the projected 2050 population of 9.6 billion); however, this depends on migration, population growth, and distribution in the future (Alcamo et al., 2007). It is expected that developing countries will continue to increase their population, using more water, not necessarily per capita, but simply because there are more people. Relative water availability (river runoff divided by population) in these locations is projected to be an average of 4.5 times lower in 2025 than in 1950 due to this growth, which doesn't begin to account for runoff changes due to climatic variation (Shiklomanov, 2000). Alcamo et al. (2007) attribute much of the decrease in water availability to climate change: as the temperature increases, evapotranspiration increases, and in some locations the increase in evapotranspiration is enough to offset an increase in precipitation, leading to a decrease in water availability despite more rainfall. However, an increase in per capita income could also play a non-insignificant role: as people individually make more money, particularly in currently low-income countries, they can afford to pay for (more) water and therefore domestic use drives an increase in withdrawals in addition to population growth and climate change (Alcamo et al., 2007).

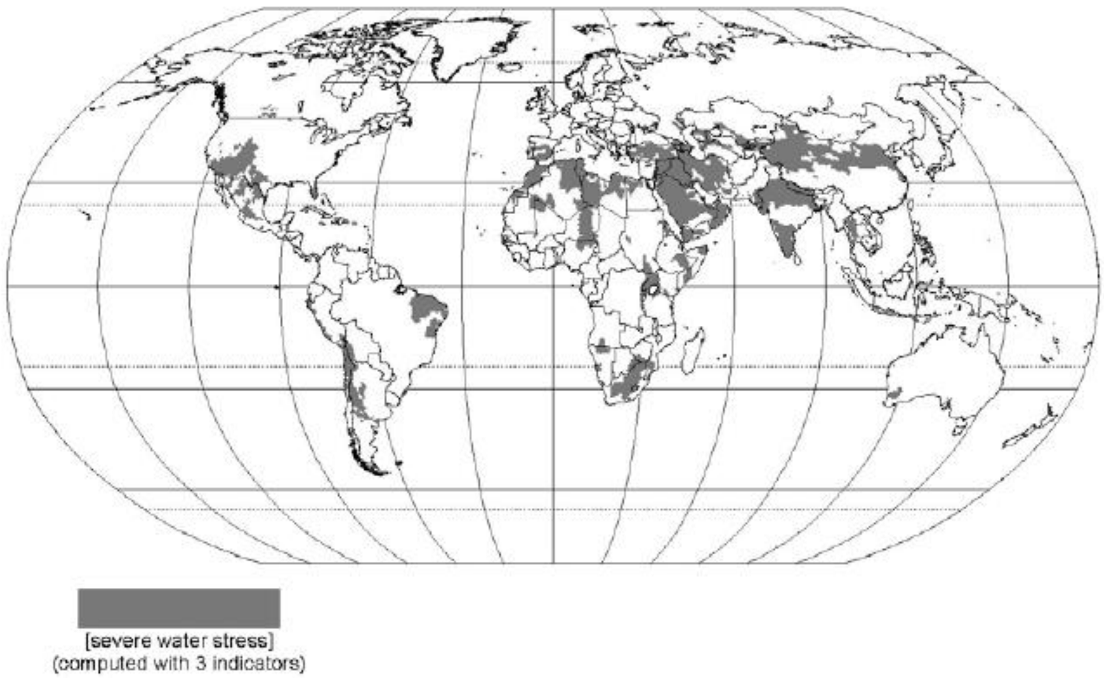

Figure 5: Locations in the world projected to be experiencing sever water stress in the 2050s under the A2 IPCC emissions scenario. In these locations, three indicators of water stress overlapped (withdrawals to availability ratio, consumption to monthly discharge ratio, and availability to population ratio) and produce reasonably accurate projections for the future, from Alcamo et al. (2007).

Haddeland et al. (2013) used results extracted from the Water Model Intercomparison Project and the Inter-Sectoral Impact Model Intercomparison Project in order to provide projections for future water availability globally based on a global projected temperature increase of 2-3 ^{o}C (as projected by the IPCC). As would be expected, anthropogenic water consumption consistently lead to a decrease in runoff. During the control period (1971-2000), human use decreased runoff by 5% or more in the Midwestern and Western United States and the mid-latitude regions of Asia (Haddeland et al., 2013). However, when anthropogenic withdrawals are removed and only climate change signals are used as factors impacting runoff, decreases are also evident in the Mediterranean, southern Australia, and Central and South America. As climate change does not affect all locations equally, there are areas that are anticipated to experience an increase in precipitation and runoff: northern latitudes, the Arabian Peninsula, India, and western Africa (Haddeland et al., 2013). Wholly, Haddeland et al. (2013) state that climate change is the globally predominant factor in causing changes to runoff, with the exception of the Nile, Colorado, and Indus River Basins. In these locations, climate change is not enough to balance anthropogenic use, and can even enhance the effect of withdrawals, resulting in larger than expected decreases in runoff (Figure 6).

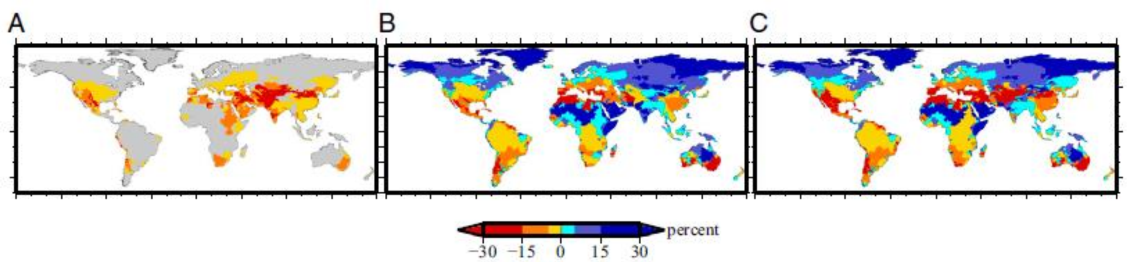

Figure 6: Comparison between how human withdrawals and climate change affect runoff in river basins globally. Panel A shows the control period (1971-2000) human impacts compared to natural simulations. Panel B shows expressed natural changes in response to a 2 K global mean temperature increase compared to control period natural simulations. Panel C shows the impact of human withdrawals in response to a 2 K global temperature increase compared to control period natural simulations, from Haddeland et al. (2013).

Runoff elasticity is a measure of how much change in runoff can be expected to accompany a certain percent change in precipitation, where higher values indicate a larger response in runoff for a certain change in precipitation (Tang and Lettenmaier, 2012). Using the 194 largest river basins in the world (supplying water to 60% of the population and 50% of the GDP), Tang and Lettenmaier (2012) found little difference in the runoff sensitivities for different IPCC emissions scenarios, but runoff elasticities varied regionally: lower values (< 1.8) were projected for the mid-latitudes of the Northern Hemisphere and higher values (> 2.2) were projected for the mid-latitudes of the Southern Hemisphere, Australia, equatorial Africa, eastern North America, and eastern Asia (Figure 7). Locally, runoff sensitivities per degree Celsius of warming range from -6% to -2%, with the highest values in eastern North America, southern Europe, and eastern Asia (Tang and Lettenmaier, 2012). Few basins in Australia, northwest Africa, and southern Asia actually experience increased runoff with temperature changes; despite higher temperatures most often being associated with more evapotranspiration, higher temperatures can sometimes lead to increased frequency of extreme precipitation (Figure 7) (Tang and Lettenmaier, 2012).

Dai et al. (2009) explained that increased runoff in central and eastern Russia cannot be explained by an increased frequency of extreme precipitation and instead is likely related to increasing local temperature. This led to decreasing snow cover and thawing permafrost, releasing water that had been held in storage for many years. As expected, trends in precipitation and local temperature from 1948 to 2004 coincide with regional runoff trends. The decrease in precipitation over Africa, southeastern Asia and eastern Australia and the increase in precipitation over the United States, Argentina, and northwestern Australia are both reflected in basin-scale runoff (Dai et al., 2009). Over this time period, effects of human activities and withdrawals on annual runoff are small compared to the effects of climate; however, accumulated over time, these small human-induced effects may result in real changes to the basins and the world's oceans (Dai et al., 2009). More recent work by Haddeland et al. (2013) confirms this result, with the understanding that in some locations, anthropogenic usage, primarily agriculture, does account for the majority of the visible changes in runoff.

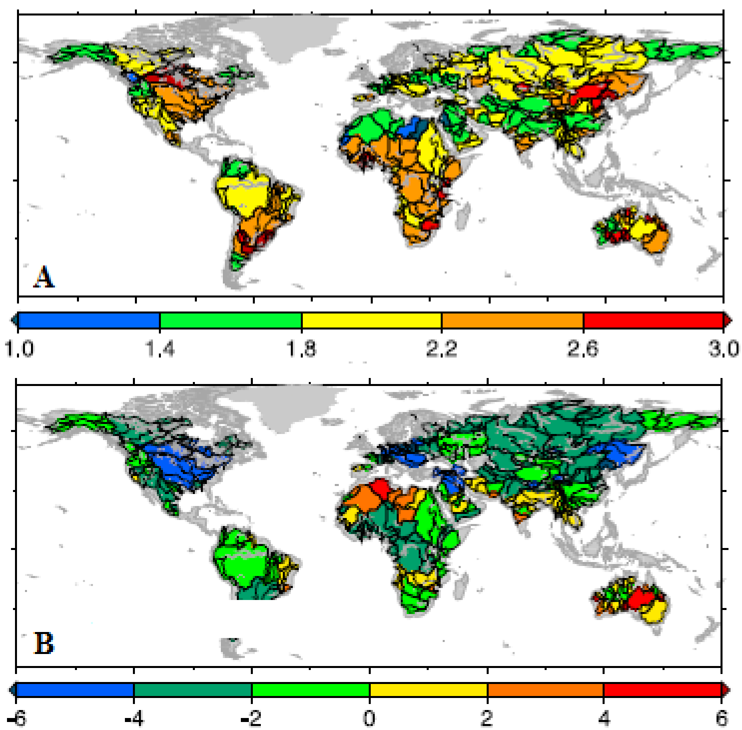

Figure 7. A. Runoff elasticities with respect to mean annual change in precipitation over 194 river basins. Higher values indicate a larger response in runoff for a certain change in precipitation. B. Runoff elasticities with respect to temperature changes (percent change in runoff per °C change in temperature), from Tang and Lettenmaier (2012).

As of 1995, the world withdrew an average of 3,790 km^3/year of water, but by 2025, average global water withdrawal is expected to reach 5,240 km^3/year (Shiklomanov, 2000). Spatially, the distribution of water withdrawals and the percentage of renewable water being withdrawn within continents is imbalanced: 95% of European withdraws are in the south and central parts of the continent, but this only accounts for about 25% of the renewable water available (Shiklomanov, 2000). In North America, 73% of total withdrawals (28% of renewable resources) are made by the United States, and 50% of African withdrawals (totaling 95% of the available renewable water in the area) are made in Northern Africa (Shiklomanov, 2000). The majority of global withdrawal and consumption takes place for agriculture in Asia, but a 150% increase in withdrawal is expected in Africa and South America by 2025 as these countries continue to develop and are able to afford more usage (Alcamo, 2007; Shiklomanov, 2000).

Globally, irrigation accounts for 69% of withdrawals (but 85% of total consumption), with the highest use regions are in southern and eastern Asia which use a combined 1676 km^3/year, the majority of which is freshwater (FAO, 2012; Hanasaki et al., 2008; Shiklomanov, 2000). Compared to Australia and New Zealand (11 km^3/year), North America (259 km^3/year) and the Middle East (231 km^3/year), the south and eastern Asia usage is over six times as high (FAO, 2012). With the exception of Europe, where most of the water withdrawals fuel industry, withdrawals in all other continents are predominated by agricultural usage. In order to sustain the population in 2050, worldwide agricultural production will need to increase by 60% (WWAP, 2015). As climate change and global warming continue, potential irrigation water consumption will increase with temperature both regionally and globally and therefore without changes in agricultural practices (shifting crow growth to regions which receive more precipitation, more efficient irrigation techniques), water needs will eventually outstrip water supply (Haddeland et al., 2013).

In the United States alone, irrigation accounts for approximately one-third of all water withdrawals and 38% of freshwater withdrawals, second only to thermoelectric power which uses 45% of all water withdrawn in the country, 73% of which was fresh surface water (USGS, 2010). Nearly 17% of water is lost before it even reaches its destination due to leaky pipes, a problem that is simple to solve, yet cost prohibitive (Fishman, 2011). Of all the states in the United States, the four states of Texas, California, Idaho, and Florida account for use of over 25% of the total water withdrawn in the nation, with irrigation dominating the usage in California (> 60%) and Idaho (81%) and thermoelectric power dominating in both Texas (45%) and Florida (61%) (USGS, 2010). By 2025, global agricultural usage is expected to utilize 1.3 times as much water and land as at present, and industrial and domestic usage are expected to increase at least 1.5 times each. Evaporation, which removes available water from the system, contributes as much to water loss as the total consumption of industrial and domestic use combined, and that value is expected to grow with increasing temperatures (Alcamo et al., 2007; Shiklomanov, 2000).

The cumulative abstraction-to-demand (CAD) ratio is used as a measure of irrigation water scarcity (Hanasaki et al., 2008). When the CAD ratio is high, water is plentiful and crops are receiving enough water, and when the CAD ratio is low, water is scarce. Haddeland et al. (2013) calculated the CAD ratio for a control period between 1971 and 2000, and found the highest value on the Indian subcontinent. Globally, the CAD ratio is expected to decease as mean temperature increases (higher temperatures are typically indicative of more evaporation and therefore less water), which has the potential to affect food production, availability, and pricing. The CAD ratio is projected to increase in only a few areas, namely western India and some small coastal areas around the globe; these are areas that are projected to experience an increase in precipitation. Though globally the CAD ratio is expected to decrease, the value of the ratio depends on the region and, therefore, overall global water consumption may not be as important to consider as seasonal and regional changes caused by consumption and the usage of dams and reservoirs (Haddeland et al., 2013).

Another useful ratio is DIA/Q, or the global domestic, industrial, and agricultural water needs over global discharge, (Vörösmarty et al., 2000). The larger the ratio (needs > discharge), the more scarce water is globally because the population needs more than it has access to in the form of river discharge. With climate change alone, DIA/Q increases by < 5%. With rising water demands only, DIA/Q increases by 50%. The combined increase is greater than the sum of its parts, 60% (Vörösmarty et al., 2000). Over each continent, climate change is only responsible for -4% to 12% of the total change, indicating that population and economic growth worldwide play a much larger role in influencing water demand. DIA/Q is fundamentally similar to the withdrawal to availability ratio (WWR) used by Hanasaki et al. (2008), and is calculated as the annual water withdrawal over runoff, or streamflow. The output is an indication of water stress, with low WWR values (<0.2) indicating low or no stress and high WWR values (>0.4) indicating high stress. Medium-high stressed areas are found in western India across the Middle East, northern Africa, the Midwestern United States, and northern China through central Asia and the population living in these stressed areas is 1.25 billion (Hanasaki et al., 2008).

These indicators are mainly calculated on an annual or global basis, but areas that experience monsoons or El Niño/La Niña conditions experience precipitation patterns that are highly variable throughout the year. The cumulative withdrawal to demand ratio (CWD) is used to determine if water needs are fulfilled on a subannual basis (Hanasaki et al., 2008). Here, higher CWD values indicate less stress and results show a different distribution of stress than indicated in the yearly WWR calculation. Seasonally stressed areas include the Sahel region of Africa, southern Africa, and the Asian monsoon region; all are areas in which there is an uneven distribution in the timing of precipitation and withdrawals (Hanasaki et al., 2008). Model results using coupled atmosphere-ocean general circulation models, global hydrological models, and IPCC emissions scenarios project that seasonal reductions in available water will also occur in in the mid-latitudes of eastern South America, the eastern United States and eastern Europe during spring Europe, western Siberia, and western North America during summer, northwestern South America in autumn, and southern Africa in winter (Hagemann et al., 2013).

Measures need to be taken if freshwater access is to be maintained in usable quantities for society. In a world with a population greater than seven billion and continuing to grow, unevenly distributed water resources that are diminishing in some of the most populated locations pose a serious threat to the current way of life. In the most densely populated regions of Asia, central and southern Europe, northern Africa and the Middle East, the amount of water that is available in rivers and in reservoirs is not enough to sustain industrial development, agriculture, and the population in the future (Shiklomanov, 2000). More developed countries inherently have a better capacity to cope with oncoming changes than do less developed countries, but even the most highly developed countries have not sustainably solved the problems associated with decreasing water availability (Milman et al., 2013).

Though economically expensive and politically difficult, agricultural and industrial practices must be made more efficient, wastewater needs to be effectively cleaned and reused (and the public needs to be convinced that “toilet to tap” does provide safe drinking water), water should be collected and stored whenever possible, river runoff should become regulated, more electricity should be provided by solar and wind power than power plants that require cooling towers, and desalination may need to become more of an option for the distant future (Fishman, 2011; IPCC, 2007; WWAP, 2015). Global warming is not likely to stop anytime soon without significant interference and regulations on emissions throughout the world. The mean global temperature will continue to rise as a result. This will alter precipitation patterns and influence evapotranspiration, bringing more water to some regions and leaving other parts of the globe highly stressed. If no measures are taken, the global water demand is projected to exceed supply by 40% as soon as 2030 (WWAP, 2015). Cooperation between nations that share the same water resources, as well as between politicians and scientists, is key to maintaining renewable water available to all.

Select Global Case Studies

Grafton et al. (2013) examined the Yellow (China), Murray-Darling (Australia), and Orange-Senqu (southern Africa) Rivers and found that median outflows for the most recent five years prior to the publishing of their paper for which data was available were only 41%, 12% and 33% of the natural outflows for each river, respectively. Though the Yellow River may have experienced a downward trend in precipitation, there has been no such change in the Murray-Darling and Orange-Senqu basins, and therefore the discrepancy in outflow is likely associated with the removal of water from the rivers for human use.

In 1949, the Yellow River provided irrigation for 0.8 million hectares, but by 1997 it irrigated over 7.5 million hectares (Grafton et al., 2013). Over this time period there has been a 35% decline in flow. The frequency of zero-flow sections of the river has increased with events starting earlier in the year and lasting longer. In 1997 alone there was no outflow into the ocean for 330 days. Some of this decline can be attributed to decreases in precipitation and increases in temperature over this time period, but the decline in flow is much more severe than the decline in rainfall, and is mainly attributable to population increase and economic development. Four rivers that feed into the Yellow River (the Kuye, Tuwei, Wuding, and Jialu Rivers) have all experienced significant decreases in runoff since the 1950s, and the Yellow River as a whole has experienced an overall decrease in annual runoff greater than 8000 km^3 in the last fifty years (Wang et al., 2011; Wu and Xia, 2014).

Furthermore, though climate change has contributed to decreasing runoff, the influence of human activity and withdrawals (agricultural, industrial, and municipal) has been increasing (Figure 8). Human activity not only has an influence on water quantity, but also on water quality: the pH of the Yellow River declined from 1992 to 2000 due to increasing emissions and the concentration of dissolved ions increased either due to increased weathering or to the concentrating of ions in less water (Wu and Xia, 2014). In 2002, changes in the operation of the Xiaolangdi Reservoir did restore some runoff and discharge to the Yellow River delta, which in turn revived biodiversity, tourism, and water supply, but outflow today is still below the natural flow of the river as recently as 50 years ago (Grafton et al., 2013). The existing water use regime along the Yellow River basin, combined with the effects of climate change and global warming could result in a 9-29% decrease in future flow of the river (Grafton et al., 2013).

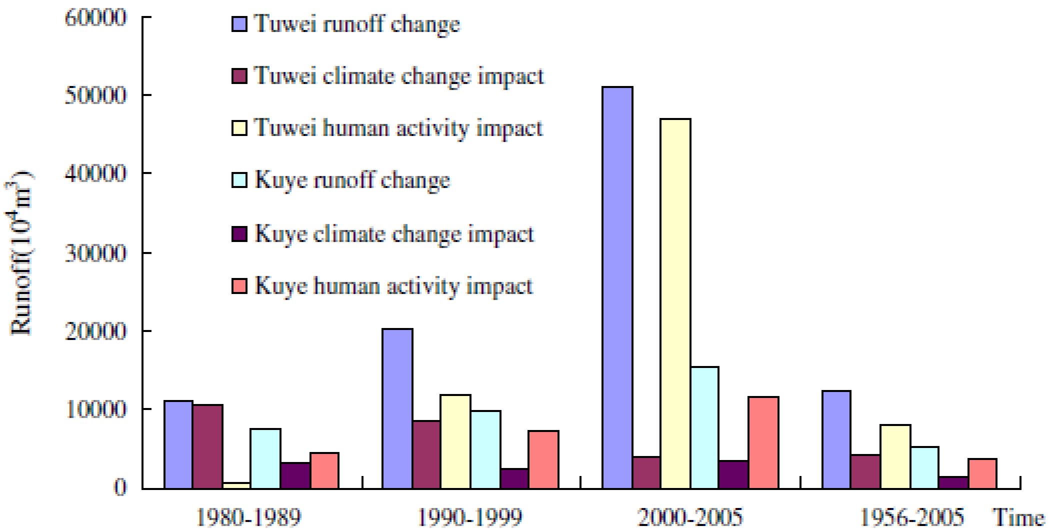

Figure 8: Change in runoff in the Tuwei and Kuye Rivers, which feed into the Yellow River, and the respective impacts of climate change and human activity on overall change, from Wang et al. (2011).

Over two million people live within and get their water from the Murray-Darling River basin in southeastern Australia, and over one million additional people living in Adelaide, just outside the basin, get their municipal water from the Murray-Darling River as well (Sullivan, 2014). Over 80% of the 1.06 million km^2 land-area in the basin is agricultural in nature (rice and cotton predominate), providing 40% of the food produced in Australia and using 60% of the nation's total agricultural water use (Grafton et al., 2013; Leblanc et al., 2012; Sullivan, 2014; Wildman Jr. and Forde, 2012). The river already experiences high variability in flow due to historic multiple-year droughts and intermittent large floods. However, irrigation still accounts for 90% of the freshwater diverted away from the river, leading floodplains along the Murray-Darling River to become dryer and the incidence of zero-flow years at the Murray River delta to increase from 1% (pre-European settlement) to over 40%; projections suggest that by 2030, zero or low flow events may increase to 69% as a result of continued water use and climate change (Grafton et al., 2013). By this time, climate change alone is projected to decrease surface water in the Murray-Darling River basin by an average of 11% (Leblanc et al., 2012).

The 1997-2009 Millennium Drought is the most severe drought on record, caused by a combination of lower than average precipitation leading to an even larger decrease in runoff (Leblanc et al., 2012). With less runoff to rely on, Australians turned to groundwater and depleted resources further (Figure 9). During this dry period, some lakes and river channels within the basin became acidic, salinity levels in a coastal lagoon nearby the river increased to five times the salinity of the ocean, and biodiversity sharply declined as a result (Grafton et al., 2013). Even prior to the drought, salinity in the basin due to irrigation, land cover change, and the deposition of windblown salts from the ocean into the basin caused degradation of water resources, biodiversity, and agricultural production (Leblanc et al., 2012). Should water become less available than it currently is, droughts like the Millennium Drought may become more normal than abnormal, salinity may increase, and resources and diversity could become more permanently damaged.

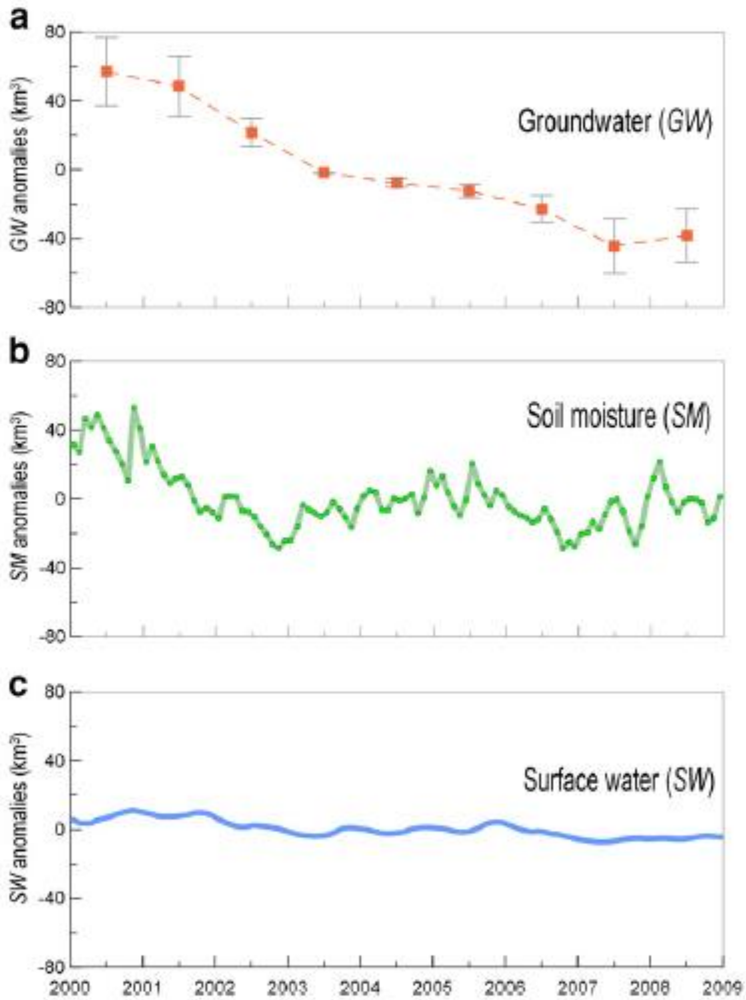

Figure 9: Changes in a) groundwater storage, b) soil moisture storage simulated by the Global Land Data Assimilation System, and c) surface water storage in the Murray-Darling River basin from 2000-2009 relative to the 2000-2008 average values. This represents the last ten years of the Millennium Drought, from Leblanc et al. (2014).

The Orange-Senqu River basin extends over 1 million km^2, covering parts of Botswana, Lesotho, Namibia, and South Africa (Kranz et al., 2010). The river has been developed for domestic, industrial, and agricultural water extractions and is a host to 31 major dams. Development is expected to continue with population growth. Endemic to development is the societal problem of waste, and water within the Orange-Senqu basin has been degraded by both industrial and municipal sewage being discharged directly into rivers (Kranz et al., 2010; Olutayo, 2012). The region is already water stressed with a per capita availability of 1000 m^3/year. Shiklomanov (2000) defines catastrophically low availability as < 1000 m^3/year per capita, very low availability as 1000 to 2100 m^3/year per capita, and low availability as 2100 to 5000 m^3/year per capita. Climate change is expected to increase this water stress by reducing precipitation, thereby reducing runoff, leaving more people with less water and leaving available water more polluted; a reduction in precipitation in Lesotho is evident as beginning in the 1960s (Earle, 2005; Olutayo, 2012). Any attempts at adapting to scarcer water conditions by increasing storage capacity may be negated if there is little water left to store (Kranz et al., 2010).

Because the Orange-Senqu River basin is spread over four countries, politics and water trading are important in the distribution of available water resources. Though Lesotho is the least politically powerful among the four countries, it historically receives the most rainfall and the resulting Lesotho Highlands Water Project (LHWP) brings in money by supplying water to South Africa. It is possible that Lesotho will also supply water to Botswana in the future, but future development in all countries depends partially on the availability of water (Earle et al., 2005). The LHWP interbasin transfer treaty was signed in 1986 and paid little attention to environmental side effects of pumping water from Lesotho to Johannesburg. Little change is likely to occur quickly, as South Africa, being the most powerful country relying on Orange-Senqu River water, does not look favorably on renegotiating water allocations (Kranz et al., 2010). The South African government created a project to understand degradation caused by the LHWP and to determine the feasibility of continuing with the LHWP in the future (Earle et al., 2005).

Within the Orange-Senqu River basin, irrigation currently accounts for one-third of the total runoff and evaporation from storage and the growth of riparian vegetation accounts for less than one-fifth (Grafton et al., 2013). As in both the Yellow and Murray-Darling Rivers, the Orange-Senqu River basin is currently experiencing water quality challenges as a result of decreased flow. This imposes a direct economic cost on the downstream population due to increased water purification costs, decreased agricultural productivity and loss of water due to dilution, as well as an environmental cost to the plants and animals that rely on riparian ecosystems for survival (Grafton et al., 2013).

In China, water-use reductions were mandated by the central government in response to a decline in flow at the mouth of the Yellow River, however, in other political climates, reallocating water to the environment may not be so simple (Grafton et al., 2013). For example, the Orange-Senqu River basin is governed by four separate countries and coordination of actions between all four countries is difficult and highly charged, particularly when the amount of rainfall reaching each country is disproportionate by size. The same is true for the Colorado River in the southwestern United States and northern Mexico. A treaty exists between the U.S. and Mexico, but if the water is not in the United States in the first place (rising temperatures, decreasing precipitation), there is little chance of Mexico being satisfied by the amount of water it receives.

Water allocations within the Murray-Darling River basin vary based on the amount of available water at a certain time. New South Wales and Victoria are each allotted half of the yearly flow of the Murray River after a percentage is delivered to South Australia (Wildman Jr. and Forde, 2012). Consumption of water is therefore seasonally based, unlike within the Colorado River, where certain amounts of water are expected despite variability in flow within the basin on an annual or sub-annual basis. The Murray-Darling River basin has also experienced some increase in environmental flow by the voluntary sale of water rights by agriculturalists to each other and the government during times of droughts. During drought, farmers who normally grew water-needy crops turned instead to selling shares of water to farmers who needed to keep livestock alive for the production of meat and dairy, and the government purchased shares in order to maintain environmental flow within the basin (Wildman Jr. and Forde, 2012). Maintaining environmental flow, though not believed to be as economically productive as agriculture, is essential to preventing further degradation of water and ecosystems. Allowing degradation to occur will negatively affect agricultural productivity in addition to recreational riverine activities that also have economic potential (Sullivan, 2014). When the Millennium drought ended, there remained little interest in maintaining reforms and an abundance of interest in returning to business as usual despite the fact that during the drought, the gross value of irrigated agricultural production was unchanged even with a 70% drop in water extractions from January 2000 to August 2007 (Grafton et al., 2013).

The Colorado River

The Colorado River basin encompasses seven states in the western and southwestern United States, divided into an Upper and Lower Basin, as well as parts of northern Mexico (Figure 10). Flow within the Colorado River mainly consists of water from snowmelt and over 90% of the flow originates from above the Grand Canyon (Arizona), indicating that areas downstream rely almost entirely on Upper Basin snowmelt. Meltwater within the river is primarily used to maintain water levels in both Lake Mead and Lake Powell, reservoirs constructed in the 1930s for the purpose of maintaining water security in the future, which provide water to cities like Las Vegas and Phoenix. Together these reservoirs increase the storage of the Colorado River Basin to four times the annual flow (Grafton et al., 2013; Wildman Jr. and Forde, 2012).

Within the United States alone, water from the Colorado River basin is used by 30 million people and 4 million acres of farmland, but by 2020, the population relying on this water is expected to reach 38 million (Belnap and Campbell, 2011; Wildman Jr., and Forde, 2012). The Colorado River flows through both the western United States and northern Mexico, making the river a shared resource. As a result, water contained within the river is allocated between both countries. The United States is obligated to provide 1,845 km^3/year of water to Mexico (Grafton et al., 2013). Paleoclimate records indicate that periods of drought, including the one occurring in the southwestern United States at present, have occurred periodically throughout the past thousand years and sustained dryness at present and in the future makes it unlikely that water deliveries stemming from the Colorado River Basin will be sustainable in the years to come (Cayan et al., 2010).

Figure 10: The Colorado River basin; the Upper Basin is outlined in red and the Lower Basin and Mexican portions of the basin shown in brown, from Belnap and Campbell (2011).

Cayan et al. (2010) identified eleven extreme drought years in the southwestern United States, three of which (2002, 2007, and 2008) occurred since the beginning of the 21st century. However these three extreme years are part of a larger drought that began in 2000, with higher than average temperatures across the entire western United States and lower than average precipitation (< 30th percentile) from the Pacific Coast to the interior of the country; this drought caused streamflow below levels of flow seen during the Dust Bowl (Belnap and Campbell, 2011). The main cause of the extreme drought in 2002 was a lack of rainfall (< 20^{th} percentile), but from 2000 to 2007, temperatures remained higher than average, peaking in 2000 and again in 2009 (Cayan et al., 2010).

Extreme drought conditions do not occur just once each year, but are rather built up over time. Two years prior to the extreme drought years since the start of the 21^{st} century, average annual runoff was only 85% of normal. One year prior, runoff averaged 81% of normal. One year after each extreme drought year, annual runoff averaged only 80% of normal (Cayan et al., 2010). These extreme conditions reach into the past and future to influence water resources and are caused by below average precipitation and above average temperatures (Figure 11). This combination can positively affect evapotranspiration and lead to below average soil moisture, which directly influences runoff, and creates a negative feedback loop (Cayan et al., 2010). By 2050, rising temperature alone is expected to cause soil moisture levels to fall below those experienced during the Dust Bowl and the southwestern drought of the early 21^{st} century and flow within the basin is projected to decrease by 5% to 20% of current levels (Belnap and Campbell, 2011).

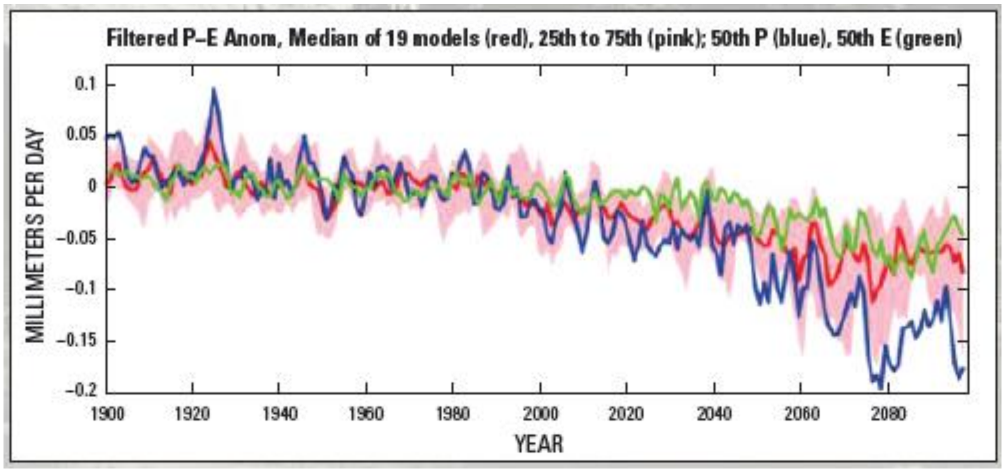

Figure 11: Modelled changes in average annual precipitation and evaporation (available runoff) in the southwestern United States through 2100. Precipitation minus evaporation averaged over nineteen separate models (red), 25th and 75th percentiles (pink), median precipitation (blue), median evaporation (green), from Belnap and Campbell (2011).

The allocation of water within the Colorado River basin is restricted to surface water (runoff), but there are groundwater resources that will likely need to be utilized if surface water allocations are continued to be met and hydropower production along the river is to remain active during times of drought. Drought began in the southwest in 2000, and by 2004, water availability from Lake Powell and Lake Mead had declined drastically. As a result, rigorous reservoir management and supplementing surface water with groundwater and surface water from other locations was necessary to deliver Colorado River promised amounts of water to promised locations and to sustain electricity production (Castle et al., 2014). Storage of freshwater within the basin declined dramatically: an average of -7.2 ± 0.8 km^3/year from December 2004 to January 2013. Data from the NASA Gravity Recovery and Climate Experiment (GRACE) measured total freshwater storage from January 2003 to November 2013 and further results from a water-balance equation showed the differences in groundwater and reservoir storage (Lake Mead and Lake Powell) over time (Figure 12) (Castle et al., 2014). Results from GRACE indicate that although surface storage in reservoirs held relatively constant, groundwater storage decreased and is currently below average because of the reliance on groundwater during times of drought (Castle et al., 2014).

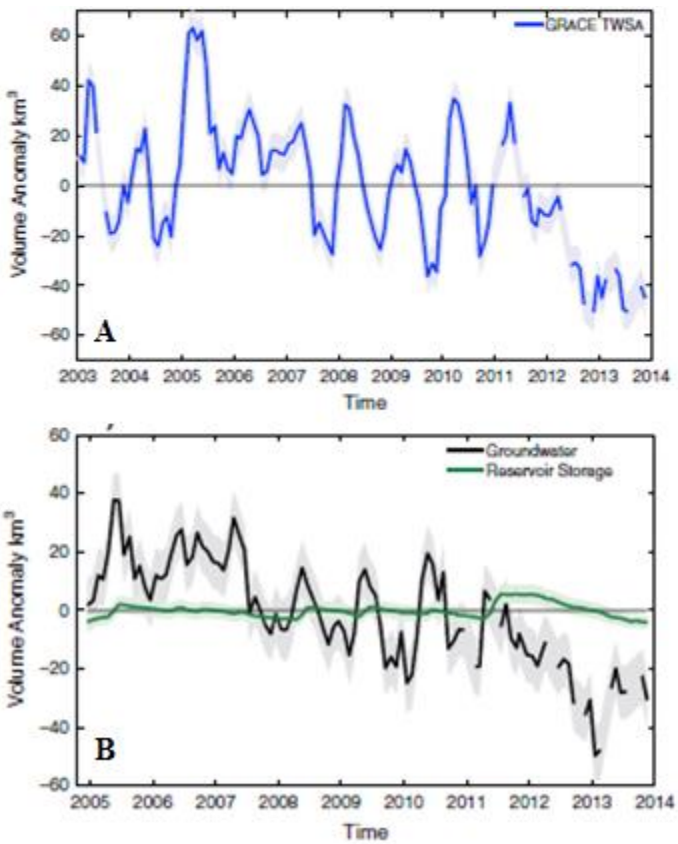

Figure 12: A. Monthly deviations in total water storage (km^3) in the Colorado River Basin from the average total water storage for the entire period (2003-2014) as measured by GRACE. B. Monthly deviations (km^3) in groundwater storage and surface water storage in reservoirs from average basin storage from December 2004 to November 2013, from Castle et al. (2014).

In 2011, the U. S. Bureau of Reclamation, which manages dams and reservoirs within the Colorado River Basin, acknowledged for the first time that demand for water exceeds the amount of available water in the basin. The Bureau cited climate change as contributing to lower runoff, with the expectation that climate change will continue to negatively impact the water regime in the future through more frequent droughts due to warming and increasing aridity, increasing evapotranspiration, and decreasing snowfall (USBR, 2011; Wildman Jr. and Forde, 2012). There are guidelines for the basin-wide distribution of water should there be a water shortage, but these are based on where water was historically attributed. A 1929 agreement states that Arizona, for example, is not allowed any water until the amount required for California has been delivered, indicating that in times of drought, the people of Arizona are much more likely to suffer than those in southern California. Furthermore, Nevada maintains a relatively constant share of the water, decreasing deliveries by only 5%, and is not as likely to suffer during a mild drought (Wildman Jr. and Forde, 2012).

For the case of prolonged drought and increasing aridity, the law requires nothing other than a meeting between the seven basin states to discuss water distribution. As a result, Arizona and Nevada both store excess water beneath the surface as groundwater as a secondary source of water, since reductions in allotted deliveries could place a significant burden upon the population. Being the farthest downstream (with the exception of Mexico) and the youngest in terms of water rights, Arizona and Nevada are in the most perilous positions in terms of water scarcity, as deliveries to other states take precedence and the likelihood of other basin states sharing the burden of water restrictions during prolonged droughts is slim (Wildman Jr. and Forde, 2012). Furthermore, since there is no unclaimed water within the Colorado River basin to supplement allocated deliveries, in times of shortage, someone is guaranteed to suffer (Schuster and Colby, 2013).

From a combination of hydrological models and global climate models, Cayan et al. (2010) project that by the second half of the 21st century, the incidence and longevity of extreme drought events will increase, with the majority of the projected droughts lasting longer than five years, and in three extreme cases lasting longer than twelve years. A drought similar to the drought of the early 21st century is likely to reoccur before 2100. The U. S. Bureau of Reclamation did not acknowledge this possibility in its guidelines for water shortages, and has likely overestimated future water supply as a result (Wildman Jr. and Forde, 2012). Soil moisture deficits are projected to reach 1.7 to 2 standard deviations below the mean as a result of elevated temperatures and increased evapotranspiration, as well as a reduction in snowpack and consequently spring meltwater, indicating that both ground and surface water storage will suffer more in the future (Barnett et al., 2008; Cayan et al., 2010). Though these results do factor in a changing climate as a result of greenhouse gas emissions (using IPCC emissions scenarios for moderately high and low emissions to the same result), the models of Cayan et al. (2010) do not take into account the effect of human withdrawals on droughts, and it can be expected that anthropogenic water withdrawals will enhance drought conditions, continue to deplete renewable water supply, and drain non-renewable groundwater from the basin (Castle et al., 2014).

There are a wide range of future projections, stemming from the use of different global climate models and different IPCC emissions scenarios, but increasing temperatures and decreasing precipitation throughout the Colorado River basin in the future are almost certain and will occur as a result of anthropogenic greenhouse gas emissions (Vano et al., 2014). The magnitude of the changes in runoff as a result of this climate change is still highly variable, but warmer temperatures are projected to result in a 5% to 45% decrease in runoff, and changes in precipitation will cause even more decline (Dawadi and Ahmad, 2012; Vano et al., 2014). This will further impact water stored within Lake Mead and Lake Powell, which could experience a 10% to 30% reduction in available water by 2060 (Dawadi and Ahmad, 2012). Additionally, if the water levels in Lake Mead fall below 320 m, hydroelectric power production at the Hoover Dam cannot continue (as of March 22, 2015, Lake Mead water elevation was 331 m), leaving up to 1.3 million people in Arizona, California, and Nevada without power and with little water (Dawadi and Ahmad, 2012; USBR, 2009). There is a 50% chance of this happening as soon as 2017 (Barnett and Pierce, 2008).

The outflow of the Colorado River at the United States-Mexican border is already only a fraction of the flow measured at Lees Ferry in Northern Arizona, and none of the water in the Colorado River at that location has reached the Gulf of California since the 1990s (Grafton et al, 2013). As a result, the Colorado River delta has shrunk to 5% of its original area and diverse native plant species have succumb to non-native, salt-tolerant species that provide little room for biodiversity. The lack of water reaching the ocean can be partially accounted for by increased evaporation, but there has been no basin-wide decrease in precipitation, and therefore the discrepancy in flow between the Colorado River at Lees Ferry and the Colorado River delta can be largely explained by water extraction for human use (Grafton et al., 2013). In May 2014, a 130 million m^3 pulse of water released from Lake Mead in March 2014 reached the Gulf of California (Voiland, 2014). This occurred because a section of Minute 319, part of the United-States Mexico Water Treaty which allows storage of Mexican water in Lake Mead, allowed an experiment to determine how the Colorado River delta would react to restored flow to occur (Flessa et al., 2013).

Environmental experiments notwithstanding, there remains a need for prolonged change within the Colorado River basin if millions of people are to retain access to freshwater, and especially if agricultural production is to continue. Already in northern Mexico the timing and amount of water supplied to farmers for irrigation is uncertain and as a result, crop yields suffer and the farmers lose money (Schuster and Colby, 2013). There are some solutions in the form of crop management (growing crops that need less water), and improving irrigation (lining canals with cement or switching to drip irrigation), but trading water rights remains a solution that could aid both the environment and the economy (Schuster and Colby, 2013). There is a history of water rights trading in the United States. In Arizona and New Mexico, water rights can be traded provided the rights were granted prior to 1919 and 1907, respectively, but the waiting period to complete the trade can take over a year (Wildman Jr. and Forde, 2012). These small transactions would need to reach a much larger area if any substantial progress is to be made in the Colorado River basin, and trades need to be able to be completed rapidly.

The success of water trading in Australia during times of drought indicates that similar trading could be successful between states in the Colorado River basin, provided standardization and regulation of trading. Like in the Murray-Darling River basin in southeastern Australia, among the Colorado River basin states there are a variety of different agricultural uses for water. Depending on the crop, trades could take place throughout the year based on who has extra availability and in the Colorado River basin there already exists the ability to transfer water between many states (Wildman Jr. and Forde, 2012). The current program of giving pre-allocated amounts of water according to seniority will not be sustainable in a more arid future, when pre-allocated amounts may no longer be available, leaving junior users with little, or no, water. However, in the interest of maintaining tradition while not losing the support of senior water rights holders, seniority could be a structural part of water trading (higher water prices for junior members) without discouraging junior members from taking part because of greater access to available water (Wildman Jr. and Forde, 2012).

Concluding Remarks

In the United States, the value of water is not always appreciated in part because water infrastructure systems and delivery have been safe and secure for many decades. Each person uses an average of 147 gallons each day, and water is a cheap commodity, more so than electricity or gasoline, adding to the misconception that water is and always will be plentiful and abundant (Barnett, 2011). Americans who live in warm climates use upwards of 67% of their total household water on landscaping and maintaining unnecessarily green yards, and the hotels and casinos of Las Vegas sport fountains the size of football fields (a city relying solely on Lake Mead and the Colorado River for water) (Barnett, 2011; Fishman 2011). Las Vegas has taken strides to encourage the use of recycled and purified wastewater in fountains and to maintain golf courses, but at least once over, this water has been removed from the system, water that could otherwise be used for electricity, irrigation, or left in place for downstream users (Fishman, 2011). A fundamental shift in the way that Americans view water will be necessary to maintain availability in the future. Having a green yard or experiencing the illusion of grandeur while on vacation in the driest large city in the nation must be balanced with the need to maintain hydroelectric power, supply homes with clean drinking water, irrigate fields to provide food to a growing population, and ideally, maintain environmental levels of flow within river basins to preserve biodiversity and riparian landscapes.

It is not just the Colorado River basin that is already experiencing a decrease in available water, but many other river basins across the globe: the Yellow River (China), the Murray-Darling River (Australia), and the Orange-Senqu River (southern Africa), for example (Grafton et al., 2013). More basins, such as those located in the Mediterranean, southern Africa, the Middle East and Arab regions, and central and southern Asia are projected to follow the same pattern of decreasing availability as climate change continues to increase temperatures and affect patterns of precipitation across the globe. Worldwide population is expected to continue growing for the foreseeable future and the need for food production will grow with the population, therefore irrigation will be increasingly necessary. As the global population grows and becomes more economically developed, so does the need for industrial and municipal water supply.

Constructed reservoirs, which ideally store multiple years' worth of water resources, provide a constantly evaporating body of water, and the levels are dictated entirely by human demand. Water can be removed from regional storage at any point, the timing and amount of which can drastically affect runoff (and therefore influence water scarcity) much more than overall global water consumption. Better reservoir management and improved irrigation are necessary to maintain adequate water resources globally, but moving food production to less water scarce regions would be a better option, though much more difficult to implement. The changes necessary to cope with the effects of declining water availability on infrastructure and water services have potentially high economic costs in the form of response strategies such as the expansion of facilities, implementing new policy, and developing new technologies (Vörösmarty et al., 2000). The consequences of not approaching the problem in a timely manner have potentially catastrophic effects: degradation of water quality and ecosystems, increased water pollution, reduction in crop production, as well as mass migration to more waterwealthy areas and conflict over water rights in international river basins (Vörösmarty et al., 2000). Adaptation, mitigation, and compensation measures are crucial to approaching water resources management now and in the future.

Public education, changes to policy, and collaboration between governmental agencies and scientists are all going to be essential to the development of strategies to manage and offset changes to water availability caused by global emissions. Therefore, a first priority should be controlling (maintaining and then decreasing) emissions, which may help curb future changes to precipitation and temperature. However, this requires global cooperation that is undeniably hard to achieve. Other management techniques include increasing the efficiency of agricultural and industrial practices, garnering public support for municipal wastewater reuse, increasing collection and storage of rainwater, regulating river runoff, and exploring alternative forms of producing electricity through solar panels and wind turbines. Desalination, which is currently used worldwide, for example in parts of Australia, Israel, and Saudi Arabia, may need to be used in other coastal locations or applied to non-traditional water resources such as those from industrial and energy-related processes (Fishman, 2011). While the readily available and accessible sources of freshwater are largely allocated to established uses, solutions in the future will likely include a range of unconventional and innovative solutions to meet and reduce demands and needs for water.

References

Alcamo, J., Flörke, M. and M. Märker (2007) Future long-term changes in global water resources driven by socio-economic and climatic changes, *Hydrological Sciences Journal*, 52(2), 247-275, doi: 10.1623/hysj.52.2.247.

Barber, N. L., (2014) Summary of estimated water use in the United States in 2010: U.S. Geological Survey Fact Sheet, 2 p. http://dx.doi.org/10.3133/fs20143109, *accessed* March 11, 2015.

Barnett, C., (2011), *Blue Revolution: Unmaking America's Water Crisis*, Beacon Press, Boston, Massachusetts, USA, 286 p.

Barnett, T. P. and D. W. Pierce, (2008), When will Lake Mead go dry?, *Water Resources Research*, 44, W03201, doi: 10.1029/2007WR006704.

Barnett, T. P., Pierce, D. W., Hidalgo, H. G., Bonfils, C., Santer, B. D., Das, T., Bala, G., Wood, A. W., Nozawa, T., Mirin, A. A., Cayan, D. R. and M. D. Dettinger, (2008), Human-induced changes in the hydrology of the western United States, *Science*, 319(5866), 1080-1083, doi: 10.1126/science.1152538.

Belnap, J. and D. H. Campbell (2011) Effects of climate change and land use on water resources in the Upper Colorado River Basin: U.S. Geological Survey Fact Sheet 2010–3123, 6 p. http://pubs.usgs.gov/fs/2010/3123/pdf /FS10-3123.pdf, accessed March 23, 2015.

Castle, S. L., Thomas, B. F., Reager, J. T., Rodell, M., Swenson, S. C. and J. S. Famiglietti (2014) Groundwater depletion during drought threatens future water security of the Colorado River Basin, *Geophysical Research Letters*, 41(16), 5904-5911, doi: 10.1002/2014GL061055.

Cayan, D. R., Das, T., Pierce, D. W., Barnett, T. P., Tyree, M. and A. Gershunov, (2010), Future dryness in the southwest US and the hydrology of the early 21st century drought, *Proceedings of the National Academy of Science*, 107(50), 21271-21276, doi: 10.1073/pnas.0912391107.

Dai, A., Qian T. and K. E. Trenberth, (2009), Changes in continental freshwater discharge from 1948 to 2004, *Journal of Climate*, 22, 2773-2792.

Dawadi, S. and S. Ahmad, (2012), Changing climatic conditions in the Colorado River Basin: Implications for water resources management, *Journal of Hydrology*, 430-431, 127-141, doi: 10.1016/j.jhydrol.2012.02.10.

Earle, A., Malzbender, D., Turton, A. and E. Manzungu (2005) A preliminary basin profile of the Orange/Senqu River, AWIRU, University of Pretoria, South Africa, 44 p. http://www.icp-confluence-sadc.org/project/docs/publicfile/id/12, *accessed* March 16, 2015.

Fishman, C., 2011, *The Big Thirst: The Secret Life and Turbulent Future of Water,* Free Press, New York City, 388 p.

Flessa, K. W., Glenn, E. P., Hinojosa-Huerta, O., de la Parra-Rentería, C. A., Ramírez-Hernández, J., Schmidt, J. C. and F. A. Zamora-Arroyo (2013) Flooding the Colorado River delta: a landscape scale experiment, *Eos*, 94(50), 485-486, doi: 10.1002/2013EO500001.

Food and Agriculture Organization of the United Nations (2012) Aquastat: water withdrawal by sector, around 2006, table, 2 p. http://www.fao.org/nr/aquastat, *accessed* March 11, 2015.

Grafton, R. Q., Pittock, J., Davis, R., Williams, J., Fu, G., Warburton, M., Udall, B., McKenzie, R., Yu, X., Che, N., Connell, D., Jiang, Q., Kompas, T., Lynch, A., Norris, R., Possingham, H. and J. Quiggin, (2013), Global insights into water resources, climate change and governance, *Nature Climate Change,* 3, 315-321, doi: 10.1038/NCLIMATE1746.
.
Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z. D., Wada, Y. and D. Wisser (2013), Global water resources affected by human interventions and climate change, *Proceedings of the National Academy of Sciences*, 111(9), 3251-3256, doi: 10.1073/pnas.1222475110.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y. and K. Tanaka (2008) An integrated model for the assessment of global water resources—Part 2: Applications and assessments, *Hydrology and Earth System Sciences*, 12(4), 1027-1037.

Hagemann, S., Chen, C., Clark, D. B., Folwell, S., Gosling, S. N., Haddeland, I., Heinke, J., Ludwig, F., Voss, F. and A. J. Wiltshite, (2013), Climate change impact on available water resources obtained using multiple global climate and hydrology models, *Earth System Dynamics*, 4, 129-144, doi: 10.5194/esd-4-129-2013.

IPCC, (2007), Summary for Policymakers. In: *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R. K. and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 1-22.

-- (2013), Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1-30, doi: 10.1017/CBO9781107415324.004.

Kranz, N., Menniken, T., and J. Hinkel, (2010), Climate change adaptation strategies in the Mekong and Orange-Senqu basins: what determines the state-of-play?, *Environmental Science and Policy*, 13, 648-659, doi: 10.1016/j.envsci.2010.09.003.

Leblanc, M., Tweed, S., Van Dijk, A., and B. Timbal, (2012), A review of historic and future hydrological changes in the Murray-Darling Basin, *Global and Planetary Change*, 80-81, 226-246, doi: 10.1016/jgloplacha.2011.10.012.

Milman, A., Bunclark, L., Conway, D., and W. N. Adger, (2013), Assessment of institutional capacity to adapt to climate change in transboundary river basins, *Climatic Change*, 121, 755-770, doi: 10.1007/s10584-013-0917-y.

Olutayo, O. A., (2012), “Mountain Watershed in Lesotho: Water Quality, Anthropogenic Impacts, and Challenges,” *Management of Mountain Watersheds*, [Krecek, J., Haigh, M. J., Hofer, T., and E. Kubin (eds).]. Springer, Dordrecht, The Netherlands, 139-149.

Schuster, E. and B. Colby, (2013), Farm and ecological resilience to water supply variability, *Journal of Contemporary Water Research and Education*, 151, 70-83.

Shiklomanov, I. A., (2000), Appraisal and assessment of world water resources, *Water International*, 25(1), 11-32.

Sullivan, C.A. (2014), Planning for the Murray-Darling Basin: lessons from transboundary basins around the world, *Stochastic Environmental Research and Risk Assessment*, 28, 123-136, doi: 10.1007/s00477-013-0789-8.

Tang, Q. and D. P. Lettenmaier, (2012), 21st century runoff sensitivities of major global river basins, *Geophysical Research Letters*, 39(6), L06403, doi: 10.1029/2011GL050834.

USBR (United States Bureau of Reclamation), (2009), Hydropower at Hoover Dam, U.S. Department of the Interior, Boulder City, Nevada, http://www.usbr.gov/lc/hoover dam/faqs/powerfaq.html, *accessed* March 23, 2015.

-- (2011), Colorado River basin water supply and demand study, interim report no. 1, executive summary, U.S. Department of the Interior, Boulder City, Nevada. http://www.usbr.gov/lc/region/programs/crbstudy/Report1/ExecSumm.pdf, *accessed* March 22, 2015.

United States Census Bureau, (2015), Countries and areas ranked by population: 2015, table, 1p. https://www,census.gov/population/international/data/countryrank/rank .php, *accessed* March 11, 2015.

Vano, J. A., Udall, B., Cayan, D. R., Overpeck, J. T., Brekke, L. D., Das, T., Hartmann, H. C., Hidalgo, H. G., Hoerling, M., McCabe, G. J., Morino, K., Webb, R. S., Werner, K., and D. P. Letternmaier, (2014), Understanding uncertainties in future Colorado River streamflow, *Bulletin of the American Meteorological Society*, 95(1), 59-78, doi: 10.1175/BAMS-D-12-00228.1.

Voiland, A. (2014) Colorado River reaches the Sea of Cortez, NASA Earth Observatory, http://earthobservatory.nasa.gov/blogs/earthmatters/2014/05/22/ colorado-river-reaches-the-sea-of-cortez/?src=eorss-blogs, *accessed* March 16, 2015.

Vörösmarty, C. J., Green, P., Salisbury, J. and R. B. Lammers, (2000), Global water resources: vulnerability from climate change and population growth, *Science*, 289(5477), 284-288.

Wang, X., Zhang, J., He, R., Angad, E., Sondoss, E., and M. Shang, (2011), A strategy to deal with water crisis under climate change for mainstream in the middle reaches of Yellow River, *Mitigation and Adaptation Strategies for Global Change*, 16, 555-566, doi: 10.1007/s11027-010-9279-1.

Wildman Jr., R. A. and N. A. Forde (2012) Management of water shortage in the Colorado River basin: evaluating current policy and the viability of interstate water trading, *Journal of the America Water Resources Association*, 48(3), 411-422.

Wu, Q. and X. Xia, (2014), Trends of water quantity and water quality of the Yellow River from 1956 to 2009: implications for the effect of climate change, *Environmental Systems Research*, 3, 6p., doi: 10.1186/2193-2697-3-1.

WWAP (United Nations World Water Assessment Programme), (2015), *The United Nations World Water Development Report 2015: Water for a Sustainable World*, Paris, UNESCO.

Vita

Megan Dunleavy Ferré grew up in Louisville, KY and attended magnet schools through high school, where the educational emphasis was on science and math. After graduation she went on to study geology at Carleton College in Northfield, MN, graduating cum laude and earning her B.A. in 2012. Following graduation, Megan moved to Kemmerer, WY to work as a park ranger at Fossil Butte National Monument, where she taught eager visitors about ancient life in a sub-tropical lake environment. One summer later, Megan was ready to head back to school and was accepted to the University of Texas at Austin to work with Dr. Joel P. Johnson. She studies hydrology and geomorphology, and is particularly frightened by predictions for what the future of the world may look like if climate change continues unabated.

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This report was typed by Megan Dunleavy Ferré.